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Physical and mechanical properties of fly ash and slag geopolymer concrete containing different types of micro-encapsulated phase change materials

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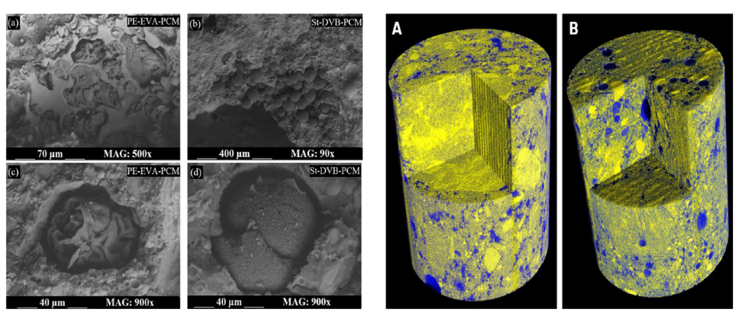
HIGHLIGHTS

- High compressive strength of fly ash/slag geopolymer concrete containing microcapsules.
- Effect of different types of micro-encapsulated phase change materials.
- Microcapsules change the workability of geopolymer concrete.
- Microcapsule addition affects the setting time of geopolymer paste.
- Shell type and agglomeration of microcapsules strongly influence the concrete properties.

GRAPHICAL ABSTRACT



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ABSTRACT

A mix design procedure for geopolymer concrete (GPC) was developed in order to maintain a high compressive strength after adding micro-encapsulated phase change materials (MPCM). The most relevant factors which affect the properties of fly ash/slag based GPC containing MPCM are considered. Class F fly ash and slag, sodium hydroxide and sodium silicates were chosen as binder and alkaline solution, respectively. Two types of MPCM were used for a better understanding the effect of different MPCMs on the properties of the GPC. The setting time of geopolymer pastes was found to depend on both the amount of water adsorbed by the microcapsules, the viscosities of the samples, and possibly the latent heat. Accordingly, the initial setting time increased and the final setting time decreased with MPCM concentration. A slump test and compressive strength measurements have been utilized to examine the workability and mechanical properties of the new mix design. It was observed that the addition of MPCM reduces the slump and the compressive strength of GPC. These effects were more pronounced for the MPCM that form agglomerated structures and has a surface containing some polar groups, than for the more spherically shaped and less agglomerated MPCM with a hydrophobic surface. Although the addition of MPCM reduced the compressive strength of geopolymer concrete, the mechanical performance was higher than that of Portland cement concrete after 28 days of curing. A combination of SEM imaging and X-ray-tomography suggested that MPCM agglomeration, gaps between MPCM and the

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concrete matrix, an increased amount of entrapped air, and microcapsules that break under stress might contribute to the reduced compressive strength of GPC.

1. Introduction

The demand for cementitious materials has increased considerably in recent years. Ordinary Portland cement is normally considered as the main material for construction purposes. However, the Portland cement production has a severe impact on the environment due to the huge amount of greenhouse gases emitted to the atmosphere [1,2]. In the early 80 s geopolymers were introduced as alternative construction materials with a lower environmental impact [3]. The geopolymer binder is synthesized by mixing materials rich in silica and amorphous alumina with a strong alkaline activator [4]. Geopolymers are a very interesting concrete alternative, with an improved performance compared to traditional concretes [5], while utilizing a high proportion of industrial by-products such as fly ash (FA), coal ash and blast furnace slag.

The incorporation of micro-encapsulated phase change materials (MPCM) in building materials, such as mortar and concrete can improve the thermal energy storage capacity of building structures, thereby decreasing the energy demand in buildings [6]. However, the presence of MPCM decreases the workability and mechanical strength of concrete [7]. In spite of reducing the concrete compressive strength by addition of MPCM, it is still often high enough to be used in building constructions.

When developing geopolymer concrete (GPC) formulations, the type, amount and ratio of the raw materials, curing time and temperature needs to be taken into account [4]. Several previous studies discuss the mix design of GPC considering the workability and strength [8,9]. However, few studies consider the properties of geopolymer compositions with incorporated MPCM [7,10]. The objective of this paper is designing a GPC mixture with improved mechanical properties and better workability, to compensate for the negative effect of incorporated MPCM on these properties. An accurate and convenient mix design method for fly ash/slag geopolymer concrete with incorporated MPCM has been developed. Since different types of MPCM may influence the GPC in different ways, two kinds of MPCMs were compared.

2. Background

In order to formulate a good GPC mix-design, it is important to know how different factors will affect the properties of fly ash/slag based GPC.

2.1. Aluminosilicate

Fly ash (FA) is considered to be one of the main sources of silica (SiO_2) and alumina (Al_2O_3) in GPC. In accordance with ASTM C618, FA is classified based on its chemical composition, where the main difference is the calcium amount. FA class C has a higher content of calcium than FA class F. A higher content of CaO in the FA results in a higher compressive strength of GPC due to the formation of hydrated products, such as calcium silicate hydrate (CSH) [11]. However, at these conditions the setting time of GPC decreases noticeably (less than 3 min) [11]. Fly ash class F has therefore been selected as a good raw material for GPC due to the lower reactivity rate, which leads to a slower setting time, convenient accessibility, and a reduced water demand [12]. In order to improve the mechanical properties of class F fly ash GPC, small amounts of other additives which are rich in CaO (e.g., blast furnace slag, silica fume, or natural pozzolan) can be added [12,13]. Ground granulated blast furnace slag (GGBFS) is one of the most common components in geopolymer mortar and concrete, due to improved mechanical and microstructural properties [12]. However, adding GGBFS causes poor workability due to a higher viscosity [14]. Chemical admixtures can be used to improve the workability of GPC.

2.2. Alkaline solution

The alkaline solution dissolves Al^{3+} and Si^{4+} ions from the aluminosilicate sources, which subsequently improves compressive strength by forming sodium aluminosilicate hydrate (NASH), calcium alumino silicate (CASH), and/or calcium silicate hydrate (CSH) gels [15]. The most common alkaline solutions are sodium hydroxide (NaOH), potassium hydroxide (KOH), sodium silicate (Na_2SiO_3) and potassium silicate (K_2SiO_3). The dissolution of fly ash and slag is dependent on the type and concentration of the alkaline solution [16]. Utilizing a sodium hydroxide alkaline solution as an alkaline activator in GPC is found to be more effective than a potassium hydroxide solution, since NaOH(aq) dissolves a higher amount of Al^{3+} and Si^{4+} ions than KOH(aq) [17]. In addition, the concentration of the alkaline solution influences the workability and compressive strength of GPC, and an optimum value of 16 M NaOH has been reported for some systems [18]. Using a combination of sodium hydroxide and sodium silicate results in a higher compressive strength than when only sodium hydroxide is used [15] due to formation of a higher amount of calcium silicate hydrate (CSH) when sodium silicate is used [15]. The ratio of sodium silicate to sodium hydroxide is important [18], since the high viscosity of sodium silicate in the alkaline solution reduces the slump of GPC in comparison with Portland cement concrete [7].

2.3. Micro-encapsulated phase change materials

The workability of concrete decreases in the presence of MPCM. This might be due to differences in the particle size of MPCM compared with the sand it replaces, or due to a reduction of available water in the sample caused by the water affinity of the MPCM shell [19]. Another possible drawback of MPCM addition to mortar or concrete is a reduction of the compressive strength [6,7,10]. However, the compressive strength is still sufficiently high for structural applications, since the acceptable range of compressive strength for building structures is normally within 25–40 MPa.

2.4. Extra water and chemical admixture

Fresh GPC possesses poor workability in comparison with fresh Portland cement concrete due to the higher viscosity of the alkaline solution. Both the workability and compressive strength of GPC are negatively influenced by the incorporation of MPCM. A better workability can be obtained by adding extra water to the mixture. However, this will reduce the compressive strength of GPC [18]. A better solution is therefore to utilize a chemical admixture. Naphthalene based superplasticizers improve the workability of fly ash class F mixtures [20]. A polycarboxylate-based superplasticizer is often the best choice for fly ash class C, due to the strong